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Accessing transversity via J/ψ production in polarized $p^\uparrow \bar{p}^\uparrow$ interactions

M. Anselmino¹, V. Barone², A. Drago³, N.N. Nikolaev^{4,5}

¹ *Dipartimento di Fisica Teorica, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*

² *Di.S.T.A., Università del Piemonte Orientale “A. Avogadro”, and INFN, Gruppo Coll. di Alessandria, 15100 Alessandria, Italy*

³ *Dipartimento di Fisica, Università di Ferrara and INFN, Sezione di Ferrara, 44100 Ferrara, Italy*

⁴ *Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*

⁵ *L.D. Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia*

Abstract

We discuss the possibility of a direct access to transversity distributions by measuring the double transverse spin asymmetry A_{TT} in $p^\uparrow \bar{p}^\uparrow \rightarrow J/\psi X \rightarrow \ell^- \ell^+ X$ processes at future GSI-HESR experiments with polarized protons and anti-protons. In the J/ψ resonance production region, with $30 \lesssim s \lesssim 45$ GeV², both the cross-section and A_{TT} are expected to be sufficiently large to allow a measurement of $h_1^q(x, M^2)$; numerical estimates are given.

1. Introduction

Transversity is the last leading-twist missing information on the quark spin structure of the nucleon [1]; whereas the unpolarized quark distributions, $q(x, Q^2)$, are well known, and more and more information is becoming available on the helicity distributions $\Delta q(x, Q^2)$, nothing is experimentally known on the nucleon transversity distribution $h_1^q(x, Q^2)$ [also denoted by $\Delta_T q(x, Q^2)$ or $\delta q(x, Q^2)$]. From the theoretical side, there exist only a few and rather preliminary models for h_1^q . The reason why h_1^q , despite its fundamental importance, has never been measured is that it is a chiral-odd function, and consequently it decouples from inclusive Deep Inelastic Scattering (DIS), which is our usual main source of information on the nucleon partonic structure. Since electroweak and strong interactions conserve chirality, h_1^q cannot occur alone, but has to be coupled to a second chiral-odd quantity.

This is possible, for example, in polarized Drell-Yan processes [2], where one measures the product of two transversity distributions, and in semi-inclusive DIS, where one couples h_1^q to a new unknown, chiral-odd, fragmentation function, the so-called Collins functions [3]. Similarly, one could couple h_1^q and the Collins function in transverse single spin asymmetries in inclusive processes like $p^\uparrow p \rightarrow \pi X$; or, one could couple h_1^q to another polarized fragmentation function by studying the spin transfer in processes like $\ell p^\uparrow \rightarrow \ell \Lambda^\uparrow X$ [4].

HERMES collaboration have measured single spin asymmetries in semi-inclusive DIS processes [5] and, together with COMPASS experiment [6], are still gathering data which should yield information on some combination of h_1^q and the Collins function. However, it will not be easy to extract information on h_1^q alone: the measured spin asymmetries can originate also from the Sivers function [7], a chiral-even spin property of quark distribution, rather than fragmentation; also, higher twist effects might still be sizeable at the Q^2 of the two experiments, thus making the interpretation of data less direct.

Measurement of transversity is planned at RHIC, in Drell-Yan processes with transversely polarized protons, $p^\uparrow p^\uparrow \rightarrow \ell^- \ell^+ X$, via the measurement of the double spin asymmetry:

$$A_{TT}^{pp} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}, \quad (1)$$

which reads at leading order

$$A_{TT}^{pp} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2) + h_1^{\bar{q}}(x_1, M^2) h_1^q(x_2, M^2) \right]}{\sum_q e_q^2 \left[q(x_1, M^2) \bar{q}(x_2, M^2) + \bar{q}(x_1, M^2) q(x_2, M^2) \right]}, \quad (2)$$

where $q = u, d, s$; M is the invariant mass of the lepton pair and \hat{a}_{TT} is the double spin asymmetry of the QED elementary process, $q \bar{q} \rightarrow \ell^- \ell^+$ [see below, Eq. (14)]. In this case one measures the product of two transversity distributions, one for a quark and one for an anti-quark. The latter (in a proton) is expected to be small; moreover, the QCD evolution of transversity is such that, in the kinematical regions of RHIC data, $h_1^q(x, Q^2)$ is much smaller than the corresponding values of $\Delta q(x, Q^2)$

and $q(x, Q^2)$. All this makes the Drell-Yan double spin asymmetry A_{TT} measurable at RHIC very small, no more than a few percents [8, 9]. This would remain true at RHIC energies even if polarized anti-protons were available [8].

One could consider the double spin asymmetry A_{TT} also for other processes, like $p^\uparrow p^\uparrow \rightarrow jet + X$, $p^\uparrow p^\uparrow \rightarrow \gamma X$, *etc.*; however, A_{TT} always turns out to be very small [10, 11], so that accessing transversity at RHIC appears as a very difficult task.

The single spin asymmetries experimentally observed in $p^\uparrow p \rightarrow \pi X$ and $\bar{p}^\uparrow p \rightarrow \pi X$ processes [12, 13, 14] can be interpreted in terms of transversity and Collins functions [15]; however, also contributions from Sivers function (with no transversity) are important [16] and these processes could hardly be used for extracting information on h_1^q alone.

Definite and direct information on transversity should be best obtained in processes and in kinematical regions such that: $h_1^q(x, Q^2)$ is sizeable, it couples to itself rather than to other unknown quantities, and the related physical observables do not receive large contributions from gluons (which do not carry any transversity). We discuss here such an ideal situation, considering the possibility – at the moment only at the stage of a proposal – of having polarized anti-protons colliding on polarized protons in the High Energy Storage Ring at GSI [17].

In the next two Sections we shall then discuss lepton pair production in $p^\uparrow \bar{p}^\uparrow$ interactions in the following kinematical region:

$$(30 \lesssim s \lesssim 45) \text{ GeV}^2; \quad M \gtrsim 2 \text{ GeV}/c^2; \quad \tau = x_1 x_2 = \frac{M^2}{s} \gtrsim 0.1. \quad (3)$$

In Section 4 we present some conclusions.

2. A_{TT} for Drell-Yan processes in $p^\uparrow \bar{p}^\uparrow$ interactions

The unpolarized Drell-Yan cross-section in $p \bar{p}$ interactions is given, at LO, by:

$$\frac{d\sigma}{d\Omega dx_1 dx_2} = \sum_q e_q^2 \left[q(x_1, M^2) q(x_2, M^2) + \bar{q}(x_1, M^2) \bar{q}(x_2, M^2) \right] \frac{d\hat{\sigma}}{d\Omega} \quad (4)$$

where

$$\frac{d\hat{\sigma}}{d\Omega} = \frac{\alpha^2}{12M^2} (1 + \cos^2 \theta) \quad (5)$$

is the cross-section for the elementary process $q \bar{q} \rightarrow \ell^- \ell^+$; θ is the production angle in the rest frame of the lepton pair (we follow the notations and geometrical configurations of Ref. [1]) and M is the invariant mass of the lepton pair. In Eq. (4) x_1 and x_2 are the usual momentum fractions carried by the (anti)quarks and all quark distributions *refer to protons* (a \bar{q} distribution inside a \bar{p} is the same as a q inside a p , *etc.*).

Usually, one integrates over all production angles of the lepton pair and uses, rather than the variables x_1 and x_2 , other physical observables like M , τ , y or x_F ,

related to x_1, x_2 by:

$$M^2 = x_1 x_2 s \equiv \tau s \quad y \equiv \frac{1}{2} \ln \frac{x_1}{x_2} \quad x_F \equiv 2 q_L / \sqrt{s} = x_1 - x_2 \quad (6)$$

$$x_1 = \frac{\sqrt{x_F^2 + 4\tau} + x_F}{2} = \sqrt{\tau} e^y \quad x_2 = \frac{\sqrt{x_F^2 + 4\tau} - x_F}{2} = \sqrt{\tau} e^{-y}, \quad (7)$$

where q_L is the longitudinal momentum of the lepton pair and \sqrt{s} is the total $p\bar{p}$ c.m. energy.

Using some of these variables Eq. (4) can be written, for example, as

$$\frac{d\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9 M^2 s (x_1 + x_2)} \sum_q e_q^2 \left[q(x_1, M^2) q(x_2, M^2) + \bar{q}(x_1, M^2) \bar{q}(x_2, M^2) \right] \quad (8)$$

with x_1, x_2 as given in Eq. (7) and $x_1 x_2 = \tau = M^2/s$.

In case of transversely polarized p and \bar{p} – therefore transversely polarized q and \bar{q} – the elementary cross-section depends also on the azimuthal angle $\varphi = \Phi - \Phi_S$, that is the difference between the azimuthal angles of the lepton pair and the proton polarization:

$$\frac{1}{2} \left[\frac{d\hat{\sigma}^{\uparrow\uparrow}}{d\Omega} - \frac{d\hat{\sigma}^{\uparrow\downarrow}}{d\Omega} \right] \equiv \frac{d\Delta\hat{\sigma}}{d\Omega} = \frac{\alpha^2}{12M^2} \sin^2 \theta \cos(2\varphi). \quad (9)$$

For the cross-section difference

$$\Delta\sigma = \frac{1}{2} \left[\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow} \right], \quad (10)$$

we have

$$\frac{d\Delta\sigma}{d\Omega dx_1 dx_2} = \sum_q e_q^2 \left[h_1^q(x_1, M^2) h_1^q(x_2, M^2) + h_1^{\bar{q}}(x_1, M^2) h_1^{\bar{q}}(x_2, M^2) \right] \frac{d\Delta\hat{\sigma}}{d\Omega}, \quad (11)$$

or

$$\begin{aligned} \frac{d\Delta\sigma}{d\varphi dM^2 dx_F} &= \frac{\alpha^2}{9 M^2 s (x_1 + x_2)} \sum_q e_q^2 \left[h_1^q(x_1, M^2) h_1^q(x_2, M^2) \right. \\ &\quad \left. + h_1^{\bar{q}}(x_1, M^2) h_1^{\bar{q}}(x_2, M^2) \right] \cos(2\varphi) \end{aligned} \quad (12)$$

where $d\Delta\hat{\sigma}/d\Omega$ is given in Eq. (9) and, again, all transversity distributions refer to protons.

Dividing (11) by (4), one gets

$$A_{TT}^{p\bar{p}} \equiv \frac{d\Delta\sigma}{d\sigma} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_1^q(x_1, M^2) h_1^q(x_2, M^2) + h_1^{\bar{q}}(x_1, M^2) h_1^{\bar{q}}(x_2, M^2) \right]}{\sum_q e_q^2 \left[q(x_1, M^2) q(x_2, M^2) + \bar{q}(x_1, M^2) \bar{q}(x_2, M^2) \right]} \quad (13)$$

where \hat{a}_{TT} is the elementary double spin asymmetry, $d\Delta\hat{\sigma}/d\hat{\sigma}$. If one detects the polar angle θ of the lepton pair one has

$$\hat{a}_{TT}(\theta, \varphi) = \frac{\sin^2 \theta}{1 + \cos^2 \theta} \cos(2\varphi), \quad (14)$$

while, when integrating over all polar angles,

$$\hat{a}_{TT}(\varphi) = \frac{1}{2} \cos(2\varphi). \quad (15)$$

Before giving numerical estimates of $A_{TT}^{p\bar{p}}$, some comments are in order.

- Drell-Yan formulas (8) and (12) are valid at leading order. It is known that NLO contributions to the Drell-Yan *cross-sections* can be large, especially at typical fixed target energies. At these energies, however, NLO corrections to the double transverse spin *asymmetry* have been found to be moderate [9]. This makes us confident that the LO accuracy adopted here can give reliable results for A_{TT} in the J/ψ region at relatively small values of s .
- Another *caveat* concerning Eqs. (8), (12) and (13) is that they are applicable in the continuum region away from resonance thresholds, and in particular above the J/ψ and ψ' peak, that is for $M \gtrsim 4 \text{ GeV}/c^2$.
- In the kinematical region we wish to explore – Eq. (3), $x_1 x_2 \gtrsim 0.1$ – sea quark and gluon contributions are negligible, hence $A_{TT}^{p\bar{p}}$ gives direct access to valence quark transversity distributions. Actually, taking into account the quark charges and the u quark dominance at large x , Eq. (13) is essentially given by

$$\frac{A_{TT}^{p\bar{p}}}{\hat{a}_{TT}} \simeq \frac{h_1^u(x_1, M^2) h_1^u(x_2, M^2)}{u(x_1, M^2) u(x_2, M^2)}. \quad (16)$$

which, at $x_1 = x_2 = \sqrt{\tau}$, gives $[h_1^u(\sqrt{\tau}, M^2)/u(\sqrt{\tau}, M^2)]^2$. Thus $A_{TT}^{p\bar{p}}$ represents a unique approach to a single transversity distribution, with no flavour admixture and no quark-antiquark entanglement.

- Exploring the large x_1, x_2 region has the clear advantage of offering a direct measurement of h_1^q ; however, it has the disadvantage of limiting such measurements to a region where, even if $A_{TT}^{p\bar{p}}$ is large, the Drell-Yan cross-sections might be too tiny; $q(x_1)$ and $q(x_2)$ in Eq. (8) are both small at large x_1, x_2 . We shall further discuss this point in the next Section.

In order to give some estimates we have computed the quantity

$$\tilde{A}_{TT}^{p\bar{p}}(M^2, x_F) \equiv \frac{A_{TT}^{p\bar{p}}}{\hat{a}_{TT}} \quad (17)$$

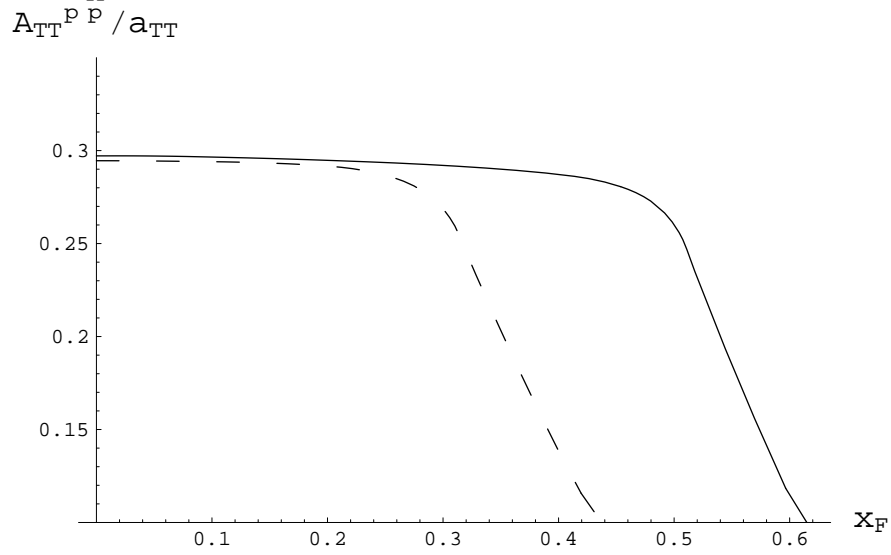


Figure 1: The $p\bar{p}$ Drell-Yan double transverse spin asymmetry $\tilde{A}_{TT}^{p\bar{p}}(M^2, x_F)$ as a function of x_F , for $M = 4 \text{ GeV}/c^2$ (solid curve: $s = 45 \text{ GeV}^2$; dashed curve: $s = 30 \text{ GeV}^2$).

as given by Eq. (13), following the procedure of Ref. [8]: one assumes, as suggested by all relativistic quark model computations [1],

$$h_1^q(x, Q_0^2) = \Delta q(x, Q_0^2) \quad h_1^{\bar{q}}(x, Q_0^2) = \Delta \bar{q}(x, Q_0^2) \quad (18)$$

at a small scale Q_0^2 , and then evolves the distributions, according to the QCD evolution of h_1 , to the desired scale M^2 . The initial parton distributions are taken from the GRV fits [20], which have indeed a small input scale, $Q_0^2 = 0.23 \text{ (GeV}/c^2)^2$.

The results are shown in Fig. 1 as a function of x_F , at $M = 4 \text{ GeV}/c^2$. The dashed curve corresponds to $s = 30 \text{ GeV}^2$, the solid curve to $s = 45 \text{ GeV}^2$. Similar results hold at larger values of M . As one can see, $\tilde{A}_{TT}^{p\bar{p}}$ is large in the kinematical region considered; notice also the flatness of $\tilde{A}_{TT}^{p\bar{p}}$ for $x_F \lesssim 0.3 - 0.5$ at fixed M^2 .

3. A_{TT} for dilepton production via J/ψ resonances in $p^\uparrow \bar{p}^\uparrow$ interactions

As we said, the Drell-Yan cross-section might be too small in the kinematical region $M \gtrsim 4 \text{ GeV}/c^2$, $30 \lesssim s \lesssim 45 \text{ (GeV)}^2$, which would offer a very good access to valence quark transversity distributions. However, it is well known [18, 19] that the cross-section for dilepton production shows a big bump around $M = 3 \text{ GeV}/c^2$, increasing by almost a factor 100 going from $M = 4 \text{ GeV}/c^2$ to $M = 3 \text{ GeV}/c^2$, due to the J/ψ and ψ' resonance production.

The total cross-section for J/ψ production in $p\bar{p}$ interactions has been measured to be [19]

$$\sigma^{p\bar{p} \rightarrow J/\psi} = (12.0 \pm 5.0) \text{ nb} \quad \text{at} \quad s = 80 \text{ (GeV)}^2. \quad (19)$$

Taking into account a 5.9% branching ratio for the $J/\psi \rightarrow e^-e^+$ (or $\mu^-\mu^+$) decay, the value (19) is big enough so that, with a luminosity of the order of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, one expects a number of $p\bar{p} \rightarrow J/\psi \rightarrow \ell^-\ell^+$ events/year of the order of 10^5 . $\sigma^{p\bar{p} \rightarrow J/\psi}$ should be approximately an order of magnitude smaller in the kinematical region (3) discussed here; more detailed evaluations can be found in Ref. [17]. These simple estimates also show how the $\ell^-\ell^+$ production in the continuum region (probably smaller by almost two orders of magnitude at $M = 4 \text{ GeV}/c^2$) might be too tiny to allow significant measurements, unless one could count on very high luminosity machines.

The question is now: how do Eqs. (8) and (13) change in the J/ψ resonance production region? From a comparison of the cross-sections measured in $p\bar{p}$ and pp collisions at $s = 80 \text{ (GeV)}^2$ [19] one would conclude that, in the energy range we are discussing, the J/ψ production is dominated by $q\bar{q}$ fusion [19]; the dilepton production in such a resonance region is described in a way analogous to the Drell-Yan continuum production, with the elementary cross-section $q\bar{q} \rightarrow \gamma^* \rightarrow \ell^-\ell^+$ simply replaced by $q\bar{q} \rightarrow J/\psi \rightarrow \ell^-\ell^+$. As J/ψ is a vector particle, like γ^* , this results in the fact that Eq. (8) applies also to the $p\bar{p} \rightarrow J/\psi \rightarrow \ell^-\ell^+$ process with the replacements [21]:

$$16\pi^2\alpha^2 e_q^2 \rightarrow (g_q^V)^2 (g_\ell^V)^2 \quad \frac{1}{M^4} \rightarrow \frac{1}{(M^2 - M_{J/\psi}^2)^2 + M_{J/\psi}^2 \Gamma_{J/\psi}^2}, \quad (20)$$

where g_q^V and g_ℓ^V are the J/ψ vector couplings to $q\bar{q}$ and $\ell^-\ell^+$. $\Gamma_{J/\psi}$ is the full width of the J/ψ and the new propagator is responsible for the large observed increase in the cross-section at $M^2 = M_{J/\psi}^2$.

The crucial point is now that, because of the identical helicity and vector structure of the γ^* and J/ψ elementary channels (all γ^μ couplings) the same replacements hold for the polarized cross-section, Eqs. (11, 12). All common factors cancel out in the ratio defining A_{TT} , so that one has for the J/ψ production region in $p\bar{p}$ processes:

$$A_{TT}^{J/\psi} = \hat{a}_{TT} \frac{\sum_q (g_q^V)^2 [h_1^q(x_1, M^2) h_1^q(x_2, M^2) + h_1^{\bar{q}}(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)]}{\sum_q (g_q^V)^2 [q(x_1, M^2) q(x_2, M^2) + \bar{q}(x_1, M^2) \bar{q}(x_2, M^2)]} \quad (21)$$

with the same \hat{a}_{TT} as given in Eqs. (14) and (15).

In the large x_1, x_2 region we are considering, the u and d valence quarks dominate; moreover, we expect the strong $q\bar{q} J/\psi$ coupling g_q^V to be the same for u and d quarks. Then Eq. (21) further simplifies into:

$$A_{TT}^{J/\psi} \simeq \hat{a}_{TT} \frac{h_1^u(x_1, M^2) h_1^u(x_2, M^2) + h_1^d(x_1, M^2) h_1^d(x_2, M^2)}{u(x_1, M^2) u(x_2, M^2) + d(x_1, M^2) d(x_2, M^2)}. \quad (22)$$

All models for the transversity distribution agree on having, at large x , $|h_1^u(x)| \gg |h_1^d(x)|$ [1], so that Eq. (21) simply amounts to

$$A_{TT}^{J/\psi} \simeq \hat{a}_{TT} \frac{h_1^u(x_1, M^2) h_1^u(x_2, M^2)}{u(x_1, M^2) u(x_2, M^2)}. \quad (23)$$

Eqs. (21-23) are the main new issues of this paper; they hold in a region where the unpolarized cross-section is large and should supply the most direct and viable way towards measuring transversity distributions.

In Fig. 2 we show $\tilde{A}_{TT}^{J/\psi}(x_F) \equiv A_{TT}^{J/\psi}/\hat{a}_{TT}$, as given by Eq. (22) ($M = 3 \text{ GeV}/c^2$), with the same choices for the distribution functions as in Fig. 1. We notice that the values of Figs. 1 and 2, that is A_{TT} from continuum Drell-Yan production at $M = 4 \text{ GeV}/c^2$ and A_{TT} via J/ψ production at $M = 3 \text{ GeV}/c^2$, are very close. This should be a well defined test for the validity of our Eqs. (21, 22): in the same region where the cross-section shows a change by almost a factor 100, the values of \tilde{A}_{TT} should hardly change.

One might wonder whether our expressions (20) and (21), which we believe to hold in general at the J/ψ peak, compare with existing models and theories for J/ψ production. The partonic structure of the asymmetry we derived, that is $\tilde{A}_{TT}^{J/\psi} \equiv A_{TT}^{J/\psi}/\hat{a}_{TT}$, is quite independent of the specific mechanism for J/ψ production, provided this process is dominated by $q\bar{q}$ annihilation, which is the case in the kinematic regime we are considering [19]. As an example of a particular mechanism of J/ψ formation, we mention the color evaporation model [22], in which an initial $q\bar{q}$ pair annihilates, via one-gluon exchange, into a final $c\bar{c}$ pair, which eventually loses its color by multiple soft gluon emission and hadronizes into a J/ψ . If we assume that the charmonium carries over the polarization of the $c\bar{c}$ pair, the resulting double spin asymmetry is exactly the one we obtained above. If, on the contrary, the polarization of the $c\bar{c}$ pair is somehow destroyed during the hadronization process, the dilepton angular distribution might be different; which means that \hat{a}_{TT} would be modified, but nonetheless $\tilde{A}_{TT}^{J/\psi}$ would remain unchanged. Incidentally, a measurement of the θ -dependence of the cross-section in the $q\bar{q}$ -dominated regime would shed light on the dynamics of J/ψ production.

4. Comments and conclusions

The double transverse spin asymmetry A_{TT} , in $p\bar{p}$ initiated Drell-Yan processes and in kinematical regions exploring the valence quark content of the proton, is a unique way of accessing directly the still unknown transversity distribution.

The problem in such a kinematical region might be the smallness of the cross-section, which would require very high luminosity beams, difficult to achieve with polarized anti-protons. This is the case of the continuum region above the J/ψ resonance production, $M \gtrsim 4 \text{ GeV}/c^2$, where the cross-section is pQCD calculable. However, as we argued above, for the purpose of measuring the transversity one could exploit also the data gathered in the J/ψ region, where the resonance plus

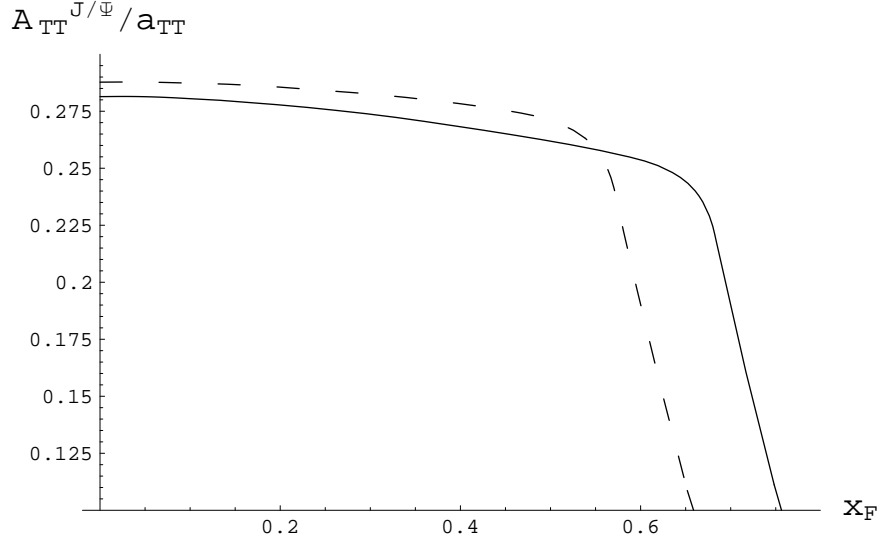


Figure 2: The double transverse spin asymmetry $\tilde{A}_{TT}^{J/\psi}$ for J/ψ production in $p\bar{p}$ collisions, as a function of x_F at $M = 3 \text{ GeV}/c^2$ (solid curve: $s = 45 \text{ GeV}^2$; dashed curve: $s = 30 \text{ GeV}^2$).

continuum cross-section is larger by almost two orders in magnitude. Specifically, we have shown that in the J/ψ resonance production region the expression of A_{TT} in terms of transversity distributions is essentially the same as in the continuum case, at least for large x values, Eqs. (16) and (23). Our numerical estimates, Figs. 1 and 2, show that A_{TT} is large. This, indeed, offers an experimentally viable and direct access to $h_1^u(x, M^2)$. Such a measurement could be performed at the proposed PAX experiment at the GSI-HESR.

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